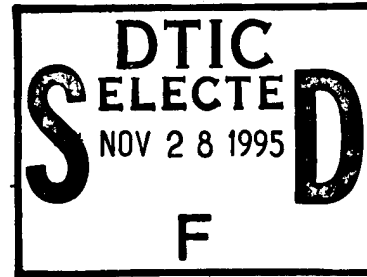


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Ice Jam Flooding on the Missouri River Near Williston, North Dakota

James L. Wuebben and John J. Gagnon

September 1995

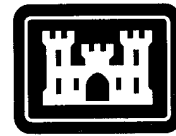


Abstract

This investigation focused on ice-related flooding along the Missouri River, just below the confluence with the Yellowstone River near Williston, North Dakota. This area is at the upper end of Lake Sakakawea. With the closure of Garrison Dam in 1953, Lake Sakakawea began filling, reaching operational levels in 1965. Changes in the hydraulics, sedimentation and ice regime of the Missouri River caused by the impoundment have led to an increase in the potential for overbank flooding. This report describes the ice regime assessment that was conducted to characterize ice jam flooding, the development of a method to predict the potential for ice jam occurrence and severity, and potential flood mitigation measures.

Cover: Spring breakup on the Yellowstone River near the confluence with the Missouri River.

For conversion of SI units to non-SI units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-93, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.



**US Army Corps
of Engineers**

Cold Regions Research &
Engineering Laboratory

Ice Jam Flooding on the Missouri River Near Williston, North Dakota

James L. Wuebben and John J. Gagnon

September 1995

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PREFACE

This report was prepared by James L. Wuebben, Research Hydraulic Engineer, and John J. Gagnon, Civil Engineering Technician, of the Ice Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided U.S. Army Engineer District, Omaha, under reimbursable work order ENH 2654, *Ice Jam Flooding Problem in the Vicinity of the Buford-Trenton Irrigation District near Williston, North Dakota*.

The authors thank Stephen L. DenHartog and Kathleen White of CRREL, and Roger L. Kay and Dwight Olson of the Omaha District for technically reviewing the report. They also thank David Deck, formerly of CRREL, and Kevin O'Brien of USAED, Omaha Williston Resource Office, for their assistance in field data collection.

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Ice Jam Flooding on the Missouri River Near Williston, North Dakota

JAMES L. WUEBBEN AND JOHN J. GAGNON

INTRODUCTION

The Buford-Trenton Irrigation District is located along the Missouri River about 15 miles upstream of the city of Williston, North Dakota, on the extreme western edge of the state. This area is at the upper end of the Garrison Dam-Lake Sakakawea Project within the Omaha District of the U. S. Army Corps of Engineers. With the closure of Garrison Dam in 1953, Lake Sakakawea began filling, reaching its maximum normal pool elevation of 1850 feet above mean sea level (msl) in 1965. Changes in the hydraulics, sedimentation and ice regime of the Missouri River caused by the impoundment of Lake Sakakawea have led to a rise in groundwater levels and an increased potential for overbank flooding

in the Buford-Trenton Irrigation District. This report describes an ice regime assessment that was conducted to characterize ice jam flooding in the vicinity of the Buford-Trenton District and to identify potential flood mitigation measures.

SITE DESCRIPTION

The Buford-Trenton Irrigation District (hereafter called the "District") was constructed in the early 1940s with joint assistance from the Bureau of Reclamation and the Department of Agriculture. The District is located approximately 170 miles upstream of Garrison Dam, at the upper end of Lake Sakakawea and just downstream of the mouth of the Yellowstone River (Fig. 1).

The District is divided by bends in the Mis-

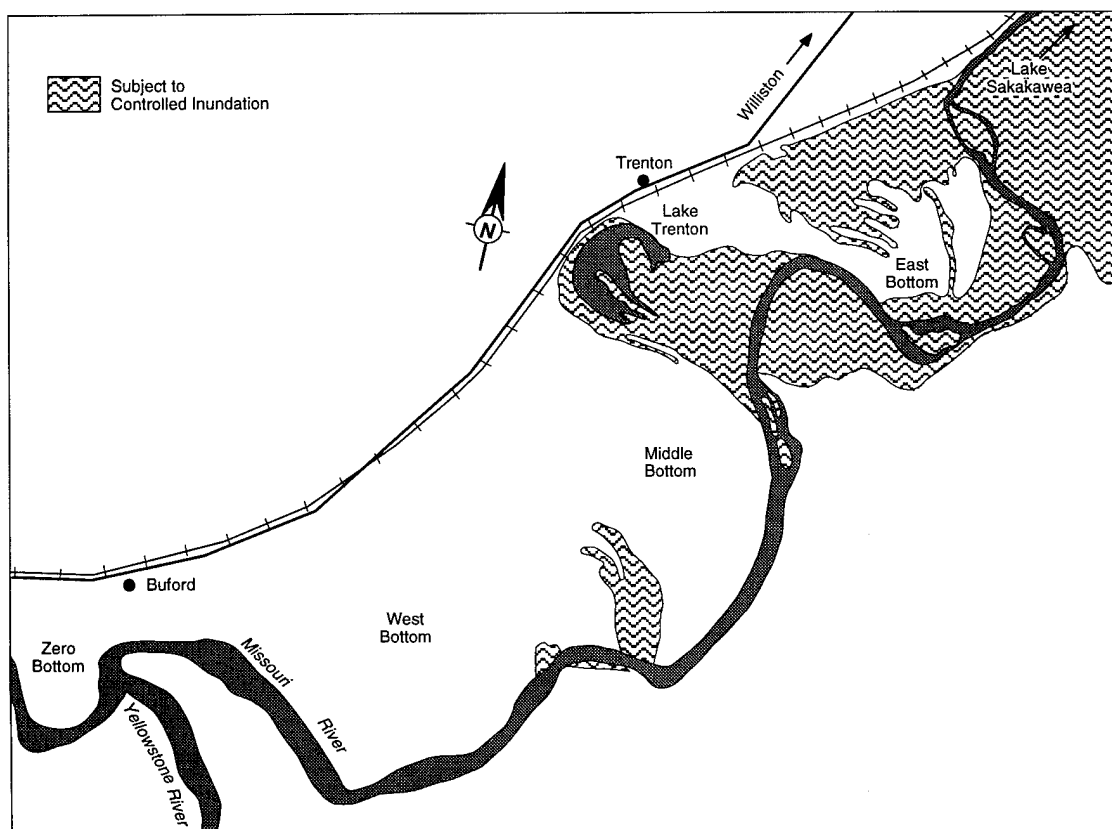


Figure 1. Location of the Buford-Trenton Irrigation District.

souri River into four areas: East, Middle, West and Zero Bottoms (Fig. 1). The following project description was taken from Design Memorandum No. MGR-146 "Buford-Trenton Irrigation District: Backwater and Drainage Problems" (USACE 1978):

The project consists of a pumping plant, the main canal and lateral system and all other features needed to deliver water to each farm unit. This also includes the drainage system carrying the return flows from the irrigated land back to the Missouri River and Lake Trenton. When fully developed the project consisted of about 16,800 acres of which 10,000 were irrigable. In 1958 the Corps acquired the East Bottom for the Garrison Dam-Lake Sakakawea project... This reduced the total acreage of the District to about 10,100 acres and the irrigated acreage to about 7100 acres.

BACKGROUND

The Missouri River above Williston has a drainage area of approximately 164,500 square miles, with roughly 70,000 square miles contributed by the Yellowstone River and 90,000 square miles by the Missouri above the confluence with the Yellowstone. The Missouri River discharge below the confluence, based on daily mean values, ranges from about 3,000 to 22,000 cfs during the fall freezeup and mid-winter periods. Mean flows for the months of December through February range from about 10,000 to 11,000 cfs. At a flow of 10,000 cfs, the Missouri River has a water surface width on the order of 500–1000 ft, a thalweg depth of 10–20 ft and water velocities of 1–3 ft/s. Water surface slopes are relatively flat (0.00002 or less) below the Route 85 bridge (cross section 1552.7). Above the Route 85 bridge the water surface slope is on the order of 0.00011, while on the lower Yellowstone River it is about 0.00018.

Hydraulics

The hydraulic analysis portion of this investigation relied heavily on the HEC-2 Water Surface Profiles computer program (USACE 1990) with the ice cover analysis option. This option provides the user with the capability to determine water surface profiles for streams with stationary floating ice covers. In addition, a utility program called ICETHK (Wuebben and Gagnon, in prep.) was employed to facilitate the use and interpretation of the HEC-2 ice option.

Verified, open-water HEC-2 data sets, obtained from the Omaha District, were employed

as the base for the ice analysis. Since the field data collection program indicated that significant ice events were driven by ice breakup on the Yellowstone River and that the ice on the Missouri River above the confluence typically ran several weeks later, the Yellowstone River HEC-2 data file was merged with the Missouri River data file at the confluence. The Missouri River above the confluence was not included in the model, except as a tributary source of water inflow.

Figure 2 shows the locations of cross sections used by the Omaha District to monitor sediment aggradation. These cross sections also correspond to some of the cross sections used to evaluate water surface profiles along the rivers using the HEC-2 computer program (USACE 1990). However, the HEC-2 data file contained several cross sections intermediate to those ranges, as well as cross sections farther downstream on the Missouri and upstream on the Yellowstone. The HEC-2 cross section numbers correspond to 1960 Missouri River mileage.

The modeled area ranged from cross section number 1497.11, which is roughly 50 miles below Williston and well into Lake Sakakawea, to 1594.38, about 10 river miles upstream of Fairview, Montana, a distance of about 100 miles. Points of interest include the Route 85 bridge at 1552.70, Hurley Bend at approximately 1570, Ryder Bend near 1578 and the Yellowstone River confluence at roughly 1582.

Hydrology

An analysis of open-water conditions along the Missouri River from Fort Peck Dam to Garrison Dam was conducted by the Omaha District (USACE 1978). USGS discharge records are available for the Missouri River at Williston for the period from 1929 to 1965, when it was discontinued. The flow record was extended through 1975 by transposing the combined flow records for the Missouri River at Culbertson, Montana, and the Yellowstone River at Sidney, Montana. The results of an annual peak discharge-frequency analysis based on those records are summarized in Table 1. The results of the 1978 discharge-frequency analysis have since been extended through 1984, again using the Culbertson and Sidney gage data. These values, also presented in Table 1, show that extending the record has resulted in a lowering of predicted discharge values, ranging from about 5% at a two-year event to 9% at the 500-year event. Both sets of values are presented for comparison, since an analysis of peak discharges occurring during

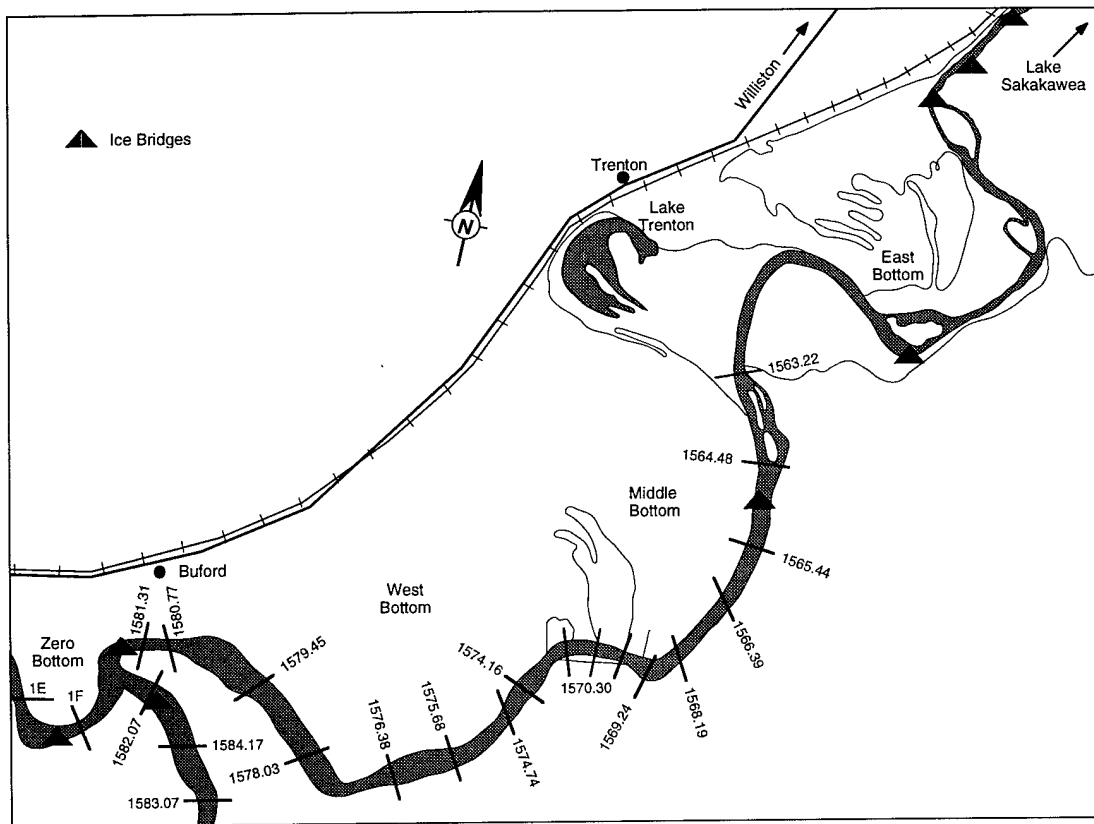


Figure 2. Details of the Buford-Trenton Irrigation District. The cross sections are the locations used by the Omaha District to monitor sediment aggradation. The locations where ice bridged across the river on 7 March 1992 are also shown.

Table 1. Missouri River discharge frequencies below the Yellowstone River confluence.

Return interval (years)	Discharge* (cfs)	Discharge† (cfs)
2	95,000	90,000
5	130,000	120,000
10	160,000	150,000
25	210,000	190,000
50	260,000	251,000
100	340,000	300,000
500	440,000	400,000

* After USACE (1978).

† Based on data provided by Roger L. Kay, Omaha District, June 1992.

the month of March contained in the 1978 report (USACE 1978) will be used later in the report.

While these discharge values are appropriate for determining open-water flood flows, the analysis of spring-breakup-related flooding requires information on flow magnitudes during past breakup events. Unfortunately the actual flows

or even the exact dates when ice cover breakup and ice jamming have occurred in the past are unknown. In the absence of more detailed historical information, spring breakup flows were taken to be the first major peaks in flow occurring during March or early April. These events may not accurately represent the date of actual ice cover breakup events and their discharge magnitudes, but they will provide a conservative estimate for use in further analysis.

The estimated breakup discharge frequencies presented in Table 2 were developed by ranking these combined flows, plotting them on log-probability paper and fitting a curve by eye. The period of record ranged from 1966, after Lake Sakakawea reached its maximum normal pool elevation, through 1990. For comparison, discharge-frequency values for peak flows in March developed by the Omaha District (USACE 1978) are also included. The March values are somewhat higher than the estimated breakup discharges since they consider the maximum discharge in the calendar month rather than the first signifi-

Table 2. Missouri River breakup discharge frequencies below the Yellowstone River confluence (USACE 1978).

<i>Return Interval (years)</i>	<i>Discharge (cfs)</i>	<i>March discharge (cfs)</i>
2	32,000	36,000
5	67,000	80,000
10	92,000	125,000
25	130,000	170,000
50	160,000	220,000
100	195,000	280,000

Table 3. Area flooded by different water stages for West Bottom and Middle Bottom. Missing values were not reported in the original reference.

<i>Elevation (ft msl)</i>	<i>West Bottom (acres)</i>	<i>Middle Bottom (acres)</i>
1858	—	0
1859	—	50
1860	0	1450
1861	—	1950
1862	200	2400
1863	—	2800
1864	450	—
1865	700	—
1866	1000	—
1868	1800	—
1870	3500	—

cant discharge peak. Further, the March discharge frequencies were developed using a log-Pearson Type III distribution rather than a log-normal distribution, and the period of record analyzed covered 1929–1975. As discussed previously, when the all-season discharge–frequency relationship was extended to cover the period from 1929 to 1984, the predicted ten-year discharge value was reduced by about 5%.

In their 1978 analysis of flooding problems within the Buford–Trenton Irrigation District (USACE 1978), the Omaha District estimated the area flooded by different water stages for the West Bottom and Middle Bottom areas. These were based on stage–discharge rating curves at HEC-2 cross sections 1563.5 and 1570.0 and topographic maps of the area. The results of this analysis are presented in Table 3.

Sedimentation

The Omaha District investigated channel aggradation in the Missouri River at the upper end of Lake Sakakawea to predict future stage–

discharge relationships at critical points along the river. These relationships are used to establish design elevations for irrigation control structures. In a report dealing with the design of channel blocks to prevent Missouri River water from backing up into the main drainage ditches of the Irrigation District (USACE 1978), the Omaha District estimated that the long-term sediment inflow for the Missouri River at Culbertson, Montana, averaged 13,500,000 tons per year, and for the Yellowstone River at Sidney, Montana, the average was 41,500,000 tons per year. The suspended sediment at the Culbertson gaging site averaged 45% sand, 50% silt and 5% clay. For the Yellowstone River at Sidney, the percentages were 35, 60 and 5%, respectively. Bed material at Culbertson had a mean grain size (D50) of 0.28 mm, while at Sidney the D50 was 0.25 mm. Based on an average deposition density of 70 lb/ft³, the measured sediment inflow rate between 1964 and 1975 was 260,000 acre-ft, or about 23,600 acre-ft/yr.

The aggradation analysis contained in the USACE (1978) report is being updated based on surveys of sediment deposits made through 1989 and a review of sediment transport data. Preliminary results of a study by the U.S. Geological Survey on the Missouri River at Bismarck, North Dakota, indicates that the procedures previously used by the Corps of Engineers for collecting and analyzing sediment load data at Bismarck, and possibly elsewhere, may have overpredicted sediment loads by an average of 30%. The updated aggradation analysis, described in a draft report (USACE 1992), found that approximately 486,000 acre-ft of sediment were deposited in the reach between the confluence and Tobacco Garden Creek (river mile 1512) between 1956 and 1988, or about 15,200 acre-ft/yr.

The deposition of sediment in the calmer headwaters of Lake Sakakawea has resulted in a progressive loss of channel capacity and an upward shift in the stage–discharge relationship for the Missouri River in the Buford–Trenton area. The Omaha District (USACE 1992) found that from 1965 through the mid-1970s, Missouri River stages for a discharge of 40,000 cfs had shifted upwards by 2.5, 3.3 and 5.0 ft at water level gages 5A, 6 and 7, respectively. Water level gage 5A is located just below the Yellowstone River confluence, near HEC-2 cross section 1581.31. Water level gage 6 is adjacent to the West Bottom at cross section 1576.38, while gage 7 is adjacent to the Middle Bottom at cross section 1566.39.

Since the mid-1970s, aggradation in the vicinity

of the Irrigation District has continued at a rate of about 1 ft per 6–7 years. Total stage increases from 1965 to 1988, for a discharge of 40,000 cfs, have been 4.6, 5.2 and 6.6 ft at Gages 5A, 6 and 7, respectively. For the period from 1988 through 2055, an additional 5–10 ft of deposition is expected to occur in the reach from the confluence of the Missouri and Yellowstone Rivers downstream through the Irrigation District to river mile 1530. Deposition depths in excess of 30 ft can be expected farther downstream. Stages, for a discharge of 40,000 cfs, are expected to rise at an average rate of 1 ft per 20 years at Gage 5A, 20 years at Gage 6, and 17 years at Gage 7. Total stage increases between 1990 and 2055 would be about 2.7, 3.2 and 3.8 ft, respectively, for Gages 5A, 6 and 7.

FIELD DATA COLLECTION

The objectives of the field program were to monitor ice, weather and runoff conditions in order to anticipate potential ice problems during the spring of 1992, and to collect additional data necessary to identify potential short- and long-term flood mitigation measures. The area studied extends along the Missouri River from Lake Sakakawea to the railroad bridge approximately 3 miles upstream of the Fort Union National Historic Site, and along the Yellowstone River upstream to Glendive, Montana.

In addition to direct measurements and observations, a significant component of the data collection involved interviews with local residents to obtain their recollections and opinions on ice-related flooding in the Buford–Trenton area. The first several site visits concentrated on gathering historical information through such discussions, while the remaining site visits focused on documenting winter ice conditions.

Historical information

Ice-related flooding tends to be local and highly site specific. While ice jams may be relatively common at a given site, they cannot be predicted with certainty in any given year, and they may be totally absent at other sites nearby. Further, ice jams often occur when flow rates are relatively low, perhaps no more than a 0.5 exceedance probability discharge,* and water levels are normally high only in the vicinity of the ice and in a backwater zone upstream. Their relatively small geographic extent (perhaps a few river miles) and short dura-

tion (from a few hours to a few days for breakup events) make it unlikely that detailed field information will have been gathered at most sites. Even in cases where hydrographic gaging records exist for a site, ice effects on the gage rating curve, the location of the gage relative to the ice accumulation, the potential for gage freezeup because of cold weather, or direct ice action on the gage can reduce its reliability for ice events.

Without prior field observation it is difficult to predict where, or even if, ice jams will form along a river. Because ice jams are site specific, it is generally not possible to extrapolate from stage data for other sites along the river. Hence, in an analysis of ice-related flooding it is often necessary to resort to other sources of historical data, sources that are often overlooked or regarded as unreliable for the analysis of open-water flooding. During this study, no significant ice run or jam occurred, and a series of interviews with local residents comprised virtually the only source of information on ice jam processes in the area.

Freezeup

A primary question asked in regard to freezeup was whether the river froze in a manner similar to a lake or a puddle, in which the ice thickens gradually and smoothly, or whether floes came floating down the river and accumulated to form a cover. A common response was that the river froze in place, leaving a smooth cover, but others recalled seeing numerous floes accumulating to form a rough cover.

Winter ice conditions

Ice conditions were reported to be generally smooth with some rough areas. Ice thickness estimates were generally on the order of 2–2.5 ft, although some residents reported thicknesses as high as 3 and 4 ft on occasion. Ice growth calculations based on thermal growth of single-layer ice indicate that the ice thickness in this area might reach 2.5 ft about once in five years, and 3 ft less than once in 50 years. The 50% exceedance ice thickness would be just over 2 ft. It is possible that these thicker estimates were made in areas where ice floes have, in some years, accumulated to form a multi-layer cover.

Breakup

It appears that, in most years, breakup on the Missouri River in the vicinity of Williston, North Dakota, is driven by events on the tributary Yellowstone River. In response to warmer weather

* This is new terminology corresponding to a recurrence interval of two years.

and increasing runoff, the ice on the Yellowstone begins to break up and run several weeks prior to breakup on the Missouri. The breakup of the Yellowstone River then proceeds downstream in a series of ice jamming and release events. Eventually the breakup front on the Yellowstone reaches the Missouri and proceeds farther downstream through the area of the Buford–Trenton Irrigation District towards Williston. During an ice run, it was reported that very large ice floes pass down river. One resident commented that the ice floes typically appeared to be 2.5–3 ft thick and “...gym-size in area.”

The ice on the Missouri River upstream of the confluence area typically remains in place for approximately two weeks after the Yellowstone River runs, in large part due to the small, steady discharges maintained by the release schedule of Fort Peck Dam in Montana. While spring runoff on the Yellowstone River rises to values on the order of 20,000–40,000 cfs, the Missouri River at Fort Peck is typically held below 10,000 cfs until after the Yellowstone River flood peak has passed.

Ice jam locations

A number of residents commented that ice jams in the vicinity of the Buford–Trenton Irrigation District form in the same locations year after year but with varying severity. Since the ice normally starts running (and jamming) on the Yellowstone River two or three weeks before the ice run begins on the Missouri River, ice runs from the upstream portion of the Missouri River were felt to be of little consequence to the Buford–Trenton area.

Once the ice run on the Yellowstone River reaches the Missouri River, it often jams in the confluence area. This jam causes few problems in the District. As on the Yellowstone River, however, the ice marches downstream in a series of jam and release events. Once a jam in the confluence area releases, subsequent jams are likely to occur in the vicinity of Ryder Point on the West Bottom (between cross sections 1576.38 and 1578.03) and the Hurley Bend in the Middle Bottom (cross section 1569.24). Ice jams were reported to be normally between 0.5 and 2.5 miles in length, but as long as 4 miles on occasion.

One resident, Clarence Johnsrud, also mentioned a former jam site between these two locations, in the bend immediately upstream of the Hurley Bend, but he stated that this ceased to be a problem when this bend was isolated by a man-made channel cutoff in 1958. This cutoff is located

between cross sections 1569.24 and 1574.16. One of the prime locations for ice jams to form is at a transition from a steeper to a milder-sloped reach. Such a cutoff channel would have significantly increased the slope within its limits but led to a significantly greater reduction in slope when the ice reached the natural channel in the Hurley Bend area. The cutoff channel could exacerbate the potential for ice jams in that lower reach.

Ice jam events

At times the dates of ice jam events estimated by local residents differed by a year or so. For example, several persons mentioned a relatively large event in the spring of 1951. However, Bob Bearce (a resident of the West Bottom) said that he knew this event had occurred in 1952 because the river was flooded on 28 March 1952—the day his son was born. In a subsequent discussion, Clarence Johnsrud (a resident of the Middle Bottom) also recalled that the event was in 1952, not 1951. This example shows that some uncertainty is to be expected, especially for events 30–40 years ago. Therefore, the dates of the ice-related events cited below may not be exact, and not all events may have been recorded.

There were six reported jams in the last 40 years. The earliest was in 1952, the most recent in 1986. Based on six jams in 40 years, the jamming frequency would be $6/40 = 0.15$, or about once in seven years. Since the backwater condition caused by the formation of Lake Sakakawea can have a significant impact on ice jam formation and since some long-past events may not have been recorded or recalled, we might instead use only the last 20 years of record. In that case, jam frequency would be $5/20$, or once in four years. Reported years with flooding included the following.

1952. According to Roger Bearce, the ice jam flood in 1952 covered much of the West Bottom. Prior to breakup the measured ice thickness was approximately 32 in., and there had still been roughly 10 in. of snow on the ground one week prior to breakup (USDOC 1953). In a review of the floods of 1952, the Weather Bureau (USDOC 1953) indicated that the peak stage of 17.76 ft at the Williston Gage occurred at 0820 on 1 April but that the ice was still moving. Flood stage for this gage was set at 20 ft. The stage had receded to 15.8 ft by 1400 but then once again rose to 16.9 ft by 1630 on the same day in response to an ice jam below the gage.

USGS records for 1 April 1952 show a mean daily flow of 124,000 cfs, but it is uncertain what

discharge was present while the jam was in place. The fact that the highest stage occurred while the ice was observed to be in motion may either indicate that the peak flow was due to the release of an upstream ice jam, in which case the flow situation was analogous to a dam-break wave, or possibly that there was an unrecorded ice jam downstream of the gage.

1972. An ice jam in March caused water to back into the main drains, flooding most of the Middle Bottom and half of the West Bottom. Thirty-one families had to move out for five days.

1975. An ice jam event occurred at some unrecorded time during the spring. Also, in June the highest open-water flood levels experienced since closure of Garrison Dam occurred.

1976. Ice scars found on trees on the Floyd Ryder property in the West Bottom (near HEC-2 cross section 1577.15) were thought by local residents to have been made during an older event, which perhaps took place in 1976. The scars were approximately 9 ft above the water surface on 26 June 1990 (determined using a hand level). Based on a HEC-2 simulation of the water surface profile for that day, the tree scars would be at an approximate elevation of 1870 ft msl. However, this elevation would also correspond to computed water levels during the 1986 event, making the true date of the scars uncertain without a tree ring analysis.

1978. High ice jam flood levels occurred in 1978. According to Clarence Johnsrud, "Larsen lost out." The Larsen property was located on the Middle Bottom. Clarence Johnsrud also recalled that although there was substantial overbank flooding, most of the ice remained in the channel in the Middle Bottom reach of river during this event.

1986. The most recent ice jam event occurred in 1986. During this event, water almost overtopped a lateral in the West Bottom near HEC-2 cross section 1578.03. A local resident recalled that it took about 11 hours from the time the initial jam formed until water reached the top of the road. Before overtopping the road on top of the lateral, however, the jam released. The ice then passed downstream and re-jammed in the Hurley Bend area in the Middle Bottom. Tree scars found in this area, which local residents suggested might have been from the 1976 event, were at an elevation of approximately 1870 ft msl. The road on top of the lateral in this area has comparable elevations, suggesting that the tree scars may have been from the 1986 event.

On 1 March 1986, water was said to have reached the top of the Borlaug Bridge on the Middle Bottom, which corresponded to an elevation of 1870 ft msl. This location coincides approximately with HEC-2 cross section 1567.44. (A Corps of Engineers survey in the spring of 1992 indicated that the top of road at this site, as defined by a photograph of the event, was about 1868.5 ft msl).

According to Bob Bearce, a resident of the Middle Bottom, the jam extended from approximately halfway between HEC-2 cross sections 1564.48 and 1565.44 to about cross section 1569.24. This would give a jam length of about 4.2 miles. He estimated that ice floes at this site were about 18 in. thick.

During June 1990, photos were taken of severely scarred trees at the Bauste property, which is downstream of the Hurley Bend on the Middle Bottom. Since that time, most of these trees have been cut down. The scars were very regular in both their orientation to the river and in the elevations of the top of scarring between numerous trees as determined by hand level. The regularity in scar orientation and elevation suggest damage by ice (or perhaps debris) rather than by animals. The scars extended from approximately 4 to 6 ft above the ground surface on a relatively level terrace near HEC-2 cross section 1564.48. The top elevation of the tree scars was approximately 1860 ft msl, which is slightly below the ground elevation at the corral buildings on the property. Local residents thought that the scars were from the 1986 ice breakup event, and water during that event was said to have come near to a corral building at the site.

Winter 1992 field observations

The plan for the 1991-92 winter field program included a series of site visits to document ice thickness and type, ice bridging and jamming locations, and other site characteristics necessary for the formulation of ice-related flooding mitigation techniques. To anticipate changing ice conditions or possible ice breakup events, we also monitored weather conditions and forecasts at Williston and several sites in Montana for any indication of an increase in runoff that could initiate breakup on either the Yellowstone or Missouri Rivers.

Winter ice conditions

Observations during 1992 showed that, with rare exceptions, the ice in the study area was a smooth, single-layer ice sheet not unlike that

formed on a lake. In some areas the ice was clear, black ice that was apparently formed in place. In other areas the ice cover was made up of large pans of ice that had formed elsewhere, floated downstream and gently accumulated through juxtaposition to form a single layer of floes, which subsequently froze together to form a smooth ice cover. Near the Fort Union trading post on the Missouri River there was some rough or lumpy ice, but it was unclear whether this resulted from upturned frazil pans or the remnants from beaver trapping activity.

By the end of January, both the Missouri and Yellowstone Rivers were almost completely ice covered, with an average thickness of 18 in. and a range of measured thickness from 13 to 21 in. On the Yellowstone River at the Route 23 bridge near Sidney, Montana, there had been a small breakup ice run, and the ice had gouged the left bank of the river. Due to subsequent warm, sunny weather and a lack of snow, these ice conditions degraded such that by the first of March there were extensive open-water areas on the Yellowstone, and the ice that remained was significantly thinner and very weak due to internal decay by solar radiation. The maximum measured ice thickness at this time was 13 in. The reduced thickness and areal extent of the ice cover meant that lesser ice volumes would be available to accumulate in an ice jam on the Missouri, and what ice remained would be quite weak. It was clear that if conditions continued as they were, the volume and strength of the ice cover would make severe ice jamming and flooding unlikely. Even if the ice cover did not melt out prior to the arrival of the spring runoff, it would have little capacity to form significant jams.

Breakup

In early March, in cooperation with Kevin O'Brien of the Corps of Engineers Williston Resource Office (WRO), several local residents were enlisted to notify us if the ice began to move. On 3 March 1992, a small, peaceful ice run was observed on the Yellowstone River upstream of Sidney, Montana, at the Seven Sisters Boat Landing. Ice downstream from this point on the Yellowstone and Missouri Rivers was extremely rotted, and numerous open leads had formed with little apparent increase in runoff.

During the morning of Saturday, 7 March 1992, the Williston Resource Office relayed a message from one of the river observers, Delbert Dishon, that ice had begun to move in the confluence area. By Sunday the Missouri River from Lake Saka-

kawea to the confluence with the Yellowstone River was essentially clear of ice. Exceptions included some small areas of shore-attached ice in shallow, slow-moving reaches and some ice floes held in place by bridge piers. Locations where ice remained bridged across the river on the morning of 7 March were recorded from the air by Kevin O'Brien of the Williston Resource Office (Fig. 2). While these bridging locations were remnant ice locations rather than ice jams, they do indicate locations of reduced ice transport capacity. Further, there were remnant ice bridges at two known jam sites, the confluence area and near the Bauste Ranch on the Middle Bottom.

Only provisional, uncorrected discharge information for the 1991-92 winter is currently available from the U.S. Geological Survey (USGS). The Omaha District's Missouri River Bulletin lists the gage on the Missouri River at Culbertson, Montana, as ice affected through 6 March. According to the USGS records, discharge peaked at 17,500 cfs on the Missouri River at Culbertson at 2300 on 5 March, while the gage on the Yellowstone River at Sidney, Montana, peaked at 18,000 cfs at 1400 on the same day. Mean daily discharges for Culbertson and Sidney on 5 March are listed as 17,200 and 8790 cfs, respectively.

Since the travel time for water passing each of these gages to reach the Buford-Trenton area is on the order of one day, these values can be used to approximate discharge on the Missouri River below its confluence with the Yellowstone River. While not exact, the flow reaching the District can be estimated by adding the mean daily values for each of the two upstream gages and adding one day to the date. Recognizing this assumption, and the fact that the flow data are still provisional, we could estimate that the Missouri River flow peaked sometime during the sixth of March and that the mean daily value was on the order of 26,000 cfs. Based on the monthly discharge-frequency analysis conducted by the Omaha District (USACE 1978), a flow peak of 26,000 cfs in the month of March would be exceeded during roughly seven out of ten years, making this a relatively common flow event.

Figure 3 shows the estimated flow record based on combining the records from the gages at Culbertson and Sidney, Montana, as described above. Since the flow records are provisional and uncorrected for ice effects, the sharp reductions in discharge on the sixth and tenth of March may be due, at least in part, to the ice cover going out near the gages at Sidney and Culbertson, respectively.

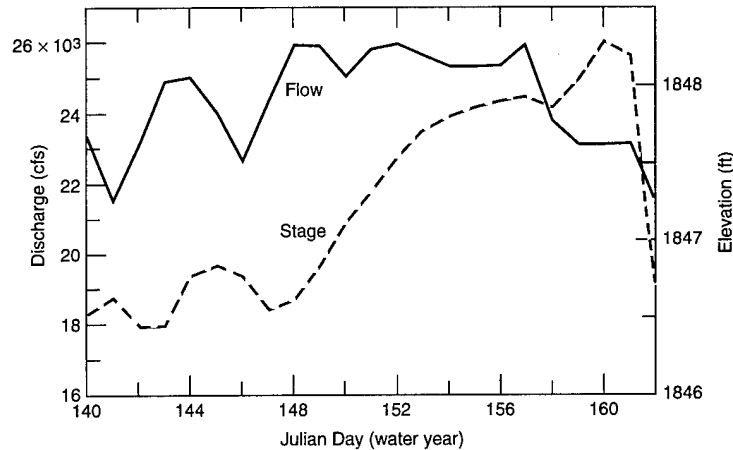


Figure 3. Flow and stage record during the 1992 breakup.

Figure 3 also shows stage data for the water level gage located at the Route 85 bridge over the Missouri River. This gage (located at HEC-2 cross section 1552.70) shows an increase in stage during the decrease in discharge beginning on 6 March, which suggests a short-term ice stoppage or jam downstream. The record also reveals a drop in stage of over 3 ft after 9 March, reflecting the release of a jam or loss of ice cover in reaches farther downstream. No gage records were available between this gage and the confluence area. Lake Sakakawea water levels during the breakup period varied gradually from 1820.8 ft msl on 3 March 1992 to 1821.2 ft msl on 9 March 1992.

The ice cover in the Buford-Trenton area went out prior to any large increase in water discharge, reflecting a loss of ice strength. No significant ice accumulations were observed, fluctuations in the water surface elevation were generally less than 3 ft, and the bulk of the fluctuations were negative, decreasing from pre-breakup levels. All flows remained well within the riverbanks, no flooding occurred and at no time was there any indication that there was a significant potential for flooding.

While it was fortunate that no damaging ice-related flood event occurred in 1992, it was unfortunate for the purposes of this study that the 1991-92 ice season was uneventful, yielding little information on the character of spring breakup on the Yellowstone and Missouri Rivers above Williston.

ANALYSIS

In contrast to open-water flooding, where high water levels directly result from excessive water discharge, ice-affected flooding results from added resistance to flow and blockage of flow caused by accumulations of ice. The formation of an ice

cover or ice jam on a river roughly doubles the wetted perimeter of a wide channel. The added resistance to flow caused by the ice cover, along with the reduction in flow area caused by the ice, results in higher stages than a comparable open-water discharge would produce. This is particularly true for ice jams, which can cause flood stages comparable to rare open-water events despite discharge recurrence intervals on the order of two years or less (exceedance probabilities on the order of 0.5 or greater).

An ice jam is defined as a stationary accumulation of fragmented ice or frazil that restricts flow (IAHR 1986). These accumulations include freezeup jams as well as breakup jams. Freezeup jams are formed by the collection of pieces of floating ice during the periods of relatively steady flow experienced when the ice cover initially forms early in the winter season. Breakup jams, on the other hand, form during the often highly unsteady flow conditions when the ice cover breaks up because of a significant rainfall, snowmelt or other increase in runoff. The longitudinal profile of a typical breakup ice jam is shown in Figure 4. In the case of the Missouri River along the Buford-Trenton Irrigation District, it is the breakup jam scenario that is of concern.

Most breakup ice jams are the result of ice moving downstream until it encounters a significant reduction in water surface slope or a strong, intact downstream ice cover or other surface obstruction. Downstream of the jam the flow may be uniform (at least in a reach-averaged sense). At the downstream end, or toe, of the jam, the ice accumulation results in a gradually varied flow profile in the transition reach as the water depth increases towards the deeper normal flow depth associated with the thicker, rougher ice conditions. If the ice

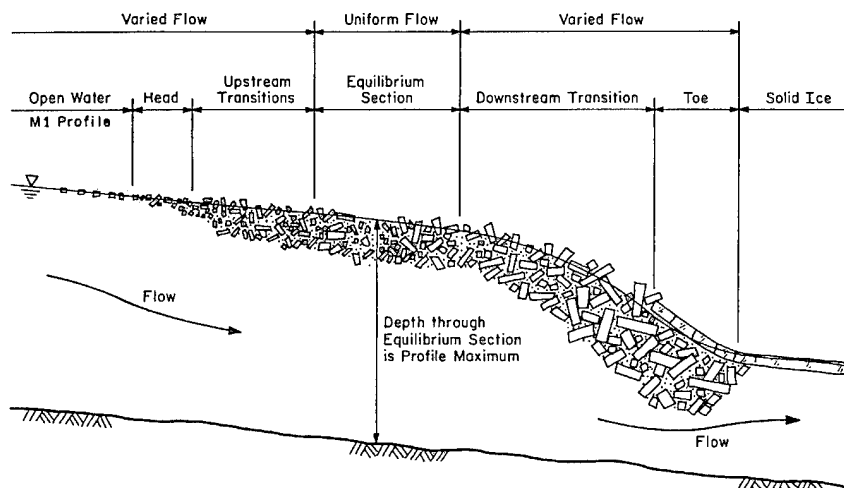


Figure 4. Longitudinal profile of a typical breakup ice jam.

jam is long enough, a fully developed or equilibrium jam reach may form, in which ice and flow conditions are relatively uniform. From the upstream end, or head, of the jam, flow depths again gradually decrease towards the lower flow depths associated with the open-water conditions upstream. Further information on ice and ice jam processes can be found in EM 1110-2-1612 (USACE 1982a).

Ice-related flooding tends to be local and highly site specific. Without prior field observations, it is difficult to predict where, or even if, ice jams will form along a river. Unfortunately no significant ice jams occurred during the current study period. Thus, analyses of ice-related flooding must rely heavily on the historical data obtained through the visits with local residents described earlier. One of the best-documented events (and also the most recent) occurred in March 1986. The jams associated with this event were severe, nearly overtopping laterals in both the Middle and West Bottoms, and they provide a good test of our ability to simulate ice jam processes in this reach of the Missouri River. The 1986 event will also provide a basis for simulating potential flood levels for other ice jam events.

Lacking field data, it is very difficult to predict where, and with what severity, jams will form along a river. Major obstacles to be overcome include estimating the appropriate ice conditions at a particular site. Analysis is often limited to estimating the upper and lower limits of probable stages. If a jam is known (or assumed) to form at a given location, it is possible to estimate the maximum resulting flood levels. It can be shown that for a given scenario of water discharge and ice conditions, the maximum water levels will occur

within the equilibrium portion of the jam described earlier. Since ice and flow conditions are relatively uniform within the equilibrium reach, it is fairly simple to estimate the water levels in this portion of the jam. Depending on where a jam forms and whether there is a sufficient upstream ice discharge to form a jam long enough to develop an equilibrium reach, actual water levels may be less and the estimate will be conservative.

March 1986 ice jam simulation

For the 1986 event we have information on the ice jam that occurred in the vicinity of Hurley Bend in the Middle Bottom. We know the maximum stage and the approximate locations of the head and toe of the jam, and we know that most of the ice remained in the channel and that the jam released while at the maximum stage. Further, knowing that the maximum stage was reached on March 1st allows us to estimate the water discharge and Lake Sakakawea stage on that day. The discharge was estimated to be 59,500 cfs on the Missouri River and 45,000 cfs on the Yellowstone River, while the Lake Sakakawea stage was taken to be 1833.2. Below the toe of the jam (cross section 1563.22), it was assumed that there was an intact ice sheet 1.5 ft thick, and above the head of the jam (cross section 1570.13) there was open water. The roughness of the ice sheet and jam were unknown, so the default values supplied by the ICETHK program (Wuebben and Gagnon, in prep.) were assumed. These values include $n = 0.025$ for sheet ice and the default n -value calculation scheme for ice jams contained in the ICETHK program. This calculation scheme is based on an empirical predictive relation developed to describe the ice accumulation roughness data of Nezhikovskiy (1964).

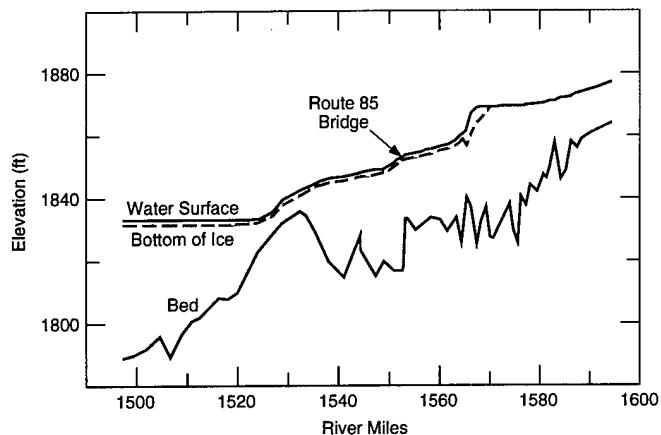


Figure 5. Simulation of the longitudinal profile of the March 1986 ice jam in the Middle Bottom area.

Using this information the HEC-2 computer program (USACE 1990) was used to calculate the resulting water surface profile as shown in Figure 5. The area of zero ice thickness, appearing as a nearly vertical line through the ice cover near HEC-2 cross section 1552.7, corresponds to the location of the Route 85 bridge. Because the HEC-2 ice option is actually a modification of the standard bridge option, ice cannot normally be simulated at cross sections where the bridge code appears in a data file. Since bridge widths are quite small relative to the river lengths typically modeled with HEC-2, the absence of ice in the bridge throat has a very localized effect on the computed water surface profile. Except in the immediate vicinity of a bridge, the effect of deleting the ice cover over such a short distance is normally negligible. Another option is to delete the bridge from the simulation if the ice effects are determined to be of greater significance.

In this jam, water reached the elevation of the road at the Borlaug Bridge site in the Middle Bottom. A Corps of Engineers survey found this location, as identified in a photograph, to have an elevation of 1868.5. Although it is difficult to determine accurately from the figure, the computed

water surface elevation at the nearest cross section to this site, 1567.44, was 1868.75 ft msl. Considering that no ice-related calibration of the open-water-verified HEC-2 data file was conducted, the agreement of the ice jam simulation with the known water surface elevation is surprisingly good.

Had we not been able to obtain information on the location of the toe of the jam, we would have had little alternative but to assume that a fragmented ice cover existed throughout the river and that it was free to thicken into an equilibrium jam in response to forces imposed by the flowing water. As described earlier, this assumption would result in the maximum possible water levels for a given discharge. A simulation of this condition was also run (Fig. 6), and the computed water surface elevation in the vicinity of the Borlaug Bridge was 1870.13. Thus, assuming a fully developed ice jam below the known (or estimated) toe of the jam resulted in a computed water surface elevation 1.38 ft higher than that computed using the known toe location. Areas closer to the toe of the jam would have been more severely affected by the difference in assumptions, while points farther upstream would have seen lesser or no effect.

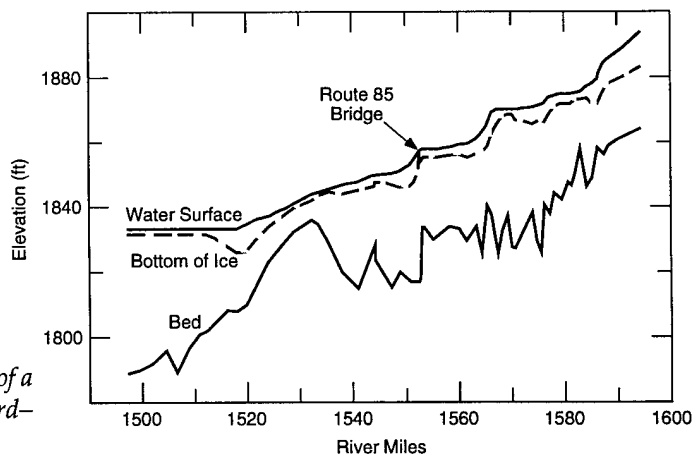


Figure 6. Simulation of the longitudinal profile of a fully developed ice jam throughout the Buford-Trenton area.

It must be reiterated that calculations assuming an equilibrium ice jam constitute the maximum possible water surface elevation for a given discharge. Actual water levels are most often less. Lower actual water levels can be found at locations close to the toe of the jam where the jam may not be fully developed. If there is enough ice to form an equilibrium jam, the actual water levels will also be lower than computed. If the discharge continues to rise or the strength of the ice accumulation deteriorates, a point can be reached where no stable jam is possible, and a lower, open-water rating curve again applies. The equilibrium model also assumes that a supply of broken ice is available. With lower discharges and stronger ice, the ice cover may remain intact and not subject to thickening into a jam.

Ice-affected water levels

The first step in the analysis of ice-affected water levels was a year-by-year review of flow records to determine the expected breakup discharge. Actual water surface profiles lie somewhere between the limiting conditions of open water, a solid cover of sheet ice and a fully developed equilibrium ice jam. The solid ice cover case would represent the minimum ice-affected stage, while the equilibrium ice jam case would represent the maximum stage possible for a given discharge. If we consider the range of possible Missouri River discharges during the breakup period, we can categorize ranges of flow from discharges too low to cause breakup of the ice cover to discharges where all ice would move downstream without jamming. These categories might be based on personal observations, observations by local residents, notes on nearby gaging records, sharp breaks in the trend of continuous stage measurements or other sources of information.

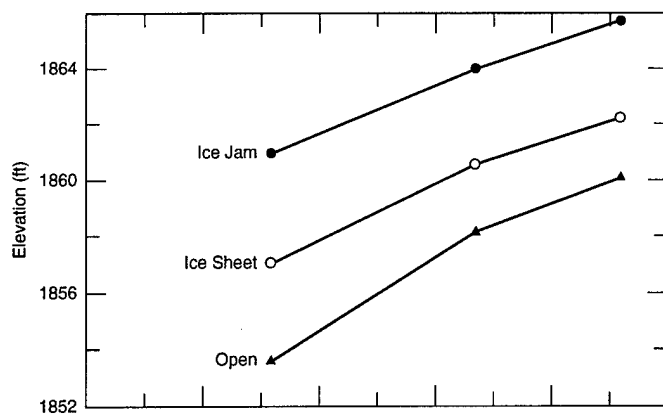
Rating curves have been developed at several locations for discharges up to 92,000 cfs. This range would include events as large as a ten-year spring ice cover breakup period flows, as well as two-year open-water flows. Figure 7 shows conditions near cross sections 1564.48 and 1568.19 in the Middle Bottom, cross section 1578.03 in the West Bottom and 1581.31 just downstream of the Yellowstone confluence area. The curves represent open-water, ice-covered and ice-jammed conditions in order of increasing stage. Based on a review of air temperature records for the winters of 1970-71 through 1991-92, it would appear that the midwinter ice thickness would normally

be greater than the 1.5-ft-thick ice measured during 1991-92 but less than the 32-in.-thick ice reported in 1952 (USDOC 1953). The ice jam curves in Figure 7 represent the maximum water surface elevations possible for the range of discharges covered, assuming that an unlimited supply of ice has formed an equilibrium jam throughout the study area.

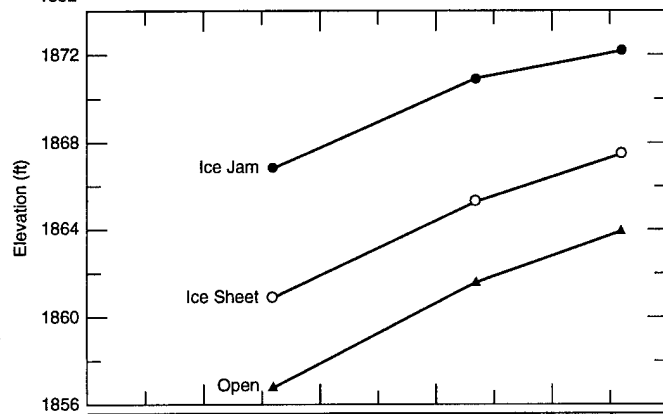
Based on a typical freezeup flow of about 10,000 cfs, a spring discharge on the order of 25,000 cfs or greater would be required to initially dislodge a strong ice cover. This value is based on a rule of thumb that the stage must rise three to four ice thicknesses above the freezeup stage to initiate the breakup and run of a strong ice cover. An increase from 10,000 to 25,000 cfs, with a continuous ice sheet, would result in an increase in stage on the order of 5 ft in most areas within the District. A deteriorated ice cover can release with lesser increases in flow, but such events do not normally result in significant ice jams. Below that discharge, then, it might be assumed that the stage-discharge relation would follow the sheet ice curve. Above that discharge, stages would tend towards the ice jam curve, assuming that conditions approaching an equilibrium jam were possible.

At a somewhat higher discharge, the trend of increasing stage with discharge would begin to flatten out. Because of the wide floodplains throughout most of the area, once the raised lateral ditches were overtopped, the channel stage would be substantially stabilized. For example, at the Borlaug Bridge we know that the 1986 jam with an estimated discharge of 59,500 cfs nearly overtopped the lateral. The stage would certainly have leveled off near the elevation of the lateral, or even dropped if the lateral had been breached, had the jam not collapsed and released. Figure 7b appears to show that the stage would continue to increase to an elevation of at least 1872 in this area, but that is due to a fairly coarse HEC-2 data file in which the apparent low elevation on the lateral is somewhat higher than that at the Borlaug Bridge. By the time the ten-year breakup period flow (or two-year open water flow) is reached, the ice jam rating curves indicate that the laterals in both the Middle and West Bottoms would be overtopped.

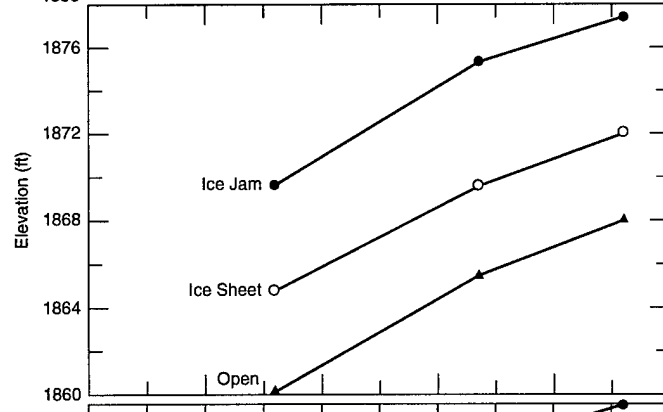
In view of the limited length of historic jams, however, actual stages for these flow ranges would likely be less than shown, since a fully developed equilibrium jam would not exist throughout the area. Most reported jams were 0.5-2.5



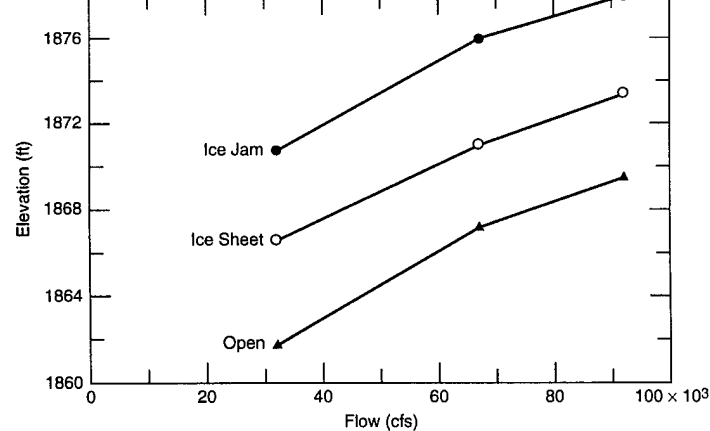
a. Cross section 1564.48.



b. Cross section 1568.19.



c. Cross section 1578.03.



d. Cross section 1581.31.

Figure 7. Rating curves for open-water, ice-covered and ice-jammed conditions.

miles long. Further, if discharge continued to increase after a jam was formed, a discharge magnitude would eventually be reached where a stable jam would no longer be possible, the jam would release and the ice would pass downstream. Stages would then return to the open-water curve. As a result, extrapolation of ice-induced stages to more extreme events is generally not reliable, particularly if such limiting factors as floodplain flow and jam release cannot be defined.

The jam release discharge remains unclear, as it depends not only on water discharge but also on the quantity of ice and the strength of the ice accumulation. In 1986 we know that two jams released with discharges no higher than about 60,000 cfs. Five of the six known jams occurred with discharges between 30,000 and 78,000 cfs. The 1952 event had a mean daily flow of 120,000 cfs and a peak discharge of 170,000 cfs in the same time frame as the jam event, but it is unclear whether the jam was still in place or had (more likely) released prior to that peak flow. Experience and data from other rivers indicate that the maximum discharge during an ice jam event is usually no more than a two-year open-water flow, which in this area would be 90,000 cfs. A ten-year breakup period discharge is approximately 92,000 cfs. It is suggested here that the maximum ice jam discharge should lie at or below this ten-year breakup period flow. Beyond that level, ice jams should become unstable, and the water levels would return to nearly open-water levels.

Ice jam potential

Although the prediction of ice jam occurrence and severity is still beyond the state of the art, it is sometimes possible to rate the likelihood of ice jams based on historical data. Such a prediction mechanism could prove useful in estimating the potential for ice jam formation in a given year, both for early warning of potential flooding and for determining whether advance measures to limit ice-related flood damage are advisable. Based on interviews with local residents and a review of literature, six historic ice jam events were identified in the Buford–Trenton area (1952, 1972, 1975, 1976, 1978 and 1986). To review the winter characteristics leading up to significant ice jam events, weather and hydrologic data from 1970 through the present were reviewed. The year preceding the closure of Garrison Reservoir, the ice jam year of 1952 and the randomly selected year of 1960 were also included.

As shown in Table 4, factors examined included freezing degree-days, snowfall, breakup period water discharge Q_b and Garrison stage. Freezing degree-days and snowfall are used to reflect the thickness and strength of ice on the river. Freezing degree-days can be used in a relatively simple equation to predict ice thickness:

$$h = c (FDD)^{0.5}$$

where h = calculated solid ice thickness

FDD = accumulated degree-days of freezing ($^{\circ}F$)

c = empirical constant to account for wind exposure and snow cover.

This constant was calibrated for the Williston area during the essentially snowless winter of 1991-92 to a value of 0.60. Using this value for the winter of 1952 resulted in a predicted ice thickness of 31 in. The measured ice thickness in 1952 was 32 in., and there was about 10 in. of snow on the ground one week prior to breakup (USDOC 1953). For winters with greater snowfall this value might overpredict ice thickness and thus may be considered conservative.

The next term in the table (FDD_{max}) is the water year Julian day (days since October 1st) when the FDD term began to decrease, taken as an indicator of net melting of the snow-ice cover. Low values of this term often indicate that the weather warmed gradually in the spring and that significant ice deterioration and melting may have occurred prior to any large increase in runoff. The term in the next column (Q_{max}) indicates the estimated date of the spring runoff causing breakup in a given year. Lacking direct field observations of ice breakup for the period of record, this term had to be estimated from discharge records, an approach that leaves some uncertainty. The date of the maximum river discharge, Q_{max} , when compared to FDD_{max} , can be used to reflect the arrival of significant spring runoff relative to warm weather in the District.

In the Williston area the local weather that governs the thickness and strength of the river ice is relatively uncoupled from the weather in the mountains that governs the snowmelt runoff that produces most breakup discharges. If the weather warms up in the Buford–Trenton area well in advance of snowmelt runoff in the mountains, the ice is likely to be too thin or rotten to pose a significant flood threat. On the other hand, an increase in runoff from upstream early in the winter may encounter a strong, resistant ice cover requiring a

Table 4. Analysis of ice jam potential for the Missouri River near the Buford-Trenton Irrigation District.

Year	Known jam	FDD (°F-days)	Calculated ice thickness (in.)	FDD _{max} (J.D.)	Q _{max} (J.D.)	Q _{max} -FDD _{max} (days)	Q _b (Kcfs)	Snow- fall (in.)	Snow timing*	Garrison stage (ft)	Σ+	Σ-	Σ±
1952	X	2750++†	31	178+	180+	2++	124.0-	25	E-	Low-	6	3	2.0
1960		2000	27	165	174	9	100.0	15--		1798.0-	1	4	0.25
1970		2030	27	182+	160	-22--	26.5	38	L+	1837.0	2	2	1.00
1971		2444	30	177+	166	-11--	58.0+	18--	L+	1842.0+	4	4	1.00
1972	X	2600++	31	160	167	7++	75.0	33		1844.0+	5	0	
1973		1650--	24	147-	157	10	30.0+	7--	E-	1843.2+	2	6	0.33
1974		2260	29	180+	186+	6++	31.0+	20		1838.8	5	0	
1975	X	1800	25	180+	175+	-5++	30.0+	48++	L+	1838.6	8	0	
1976	X	1800	25	165	175+	10	43.0+	28	E-	1840.5+	3	1	3.00
1977		1900	26	140-	170	30--	25.0	15--	E-	1836.0	0	6	--
1978	X	3000++	33	170+	176+	6++	87/0	15	E	1828.0-	6	4	1.50
1979		3300++	34	180+	170	-10--	60.0+	37	L+	1835.5	5	1	2.50
1980		1100	26	165	151-	-14--	26.0	25		1837.6	0	3	--
1981		1100--	20	135-	145-	10	28.0	5--	E-	1829.9	0	8	--
1982		2300	29	160	147-	-13--	40.0+	60++	L+	1829.2-	4	4	1.00
1983		1422--	23	174+	166	-8	21.0-	29	VL+	1841.1+	3	3	1.00
1984		1960	27	168+	174+	6++	19.5	30	L+	1839.1	5	1	5.00
1985		2307	29	158	156	-2++	25.0	18--	L+	1838.4	3	3	1.00
1986	X	2000	27	145-	152-	7++	59.5+	35	L+	1836.3	4	2	2.00
1987		1018--	19	179+	168	-11--	17.0	16--	E-	1840.3+	2	6	0.33
1988		1517--	23	167+	176+	9	17.0-	16--	E-	1832.9-	2	7	0.29
1989		2300	29	175+	167	-8	40.5+	32	E-	1820.7-	2	2	1.00
1992		918--	18	147-	158	11--	26.0	<18--	E-	1821.5	0	9	--

* E = early, L = late, VL = very late.

† + = high correlation with ice jamming, - = lower correlation with ice jamming.

greater, more rapid discharge increase to initiate breakup.

As mentioned previously, it takes a certain magnitude of discharge and stage increase to release an ice cover and allow it to move downstream. If the increase in discharge is rapid or the ice is deteriorated, the required increase in stage may be slight, but for gradually rising discharges the required increase in stage may be equivalent to three or four ice thicknesses. For the typical freezeup and midwinter discharge of about 10,000 cfs in the study area, a spring runoff event in excess of 25,000 cfs should be required to break up a strong ice cover. The required breakup discharge (Q_b) varies, however, with the actual freezeup discharge for a given year, as well as variations in the other terms listed in Table 4. At very high discharges, greater than about 90,000 cfs, no stable ice jams would be able to form. The situation would then revert to an open-water flood scenario.

Two terms are included to account for snowfall characteristics. Ideally the snow-related portion of the prediction scheme would use the depth of snow remaining on the ground prior to breakup as an index, but historic records of this parameter are not available. Instead we have used two terms,

the total snowfall for the season and the timing of the snowfall, as an indicator. The timing of the snowfall is listed as being E for early, L for late or VL for very late. The climate of the Williston area is such that, in many years, the snow has completely melted from the river ice surface prior to breakup. In addition to potential thinning of the ice cover through thermal melting, this allows solar radiation to penetrate and decay the internal structure of the ice. In this manner, even a relatively thick ice cover can be weakened to reduce or eliminate the ice jam flooding potential.

A factor is also included in the table to reflect the elevation of Lake Sakakawea (Garrison Reservoir stage), since the most common location for ice jam formation is the transition from a steeper to a milder energy slope such as that presented by a river flowing into a lake or reservoir. Garrison Reservoir reached its normal operating levels in 1965 and since that time has been a potential factor in the occurrence and location of ice jam formation.

In addition to listing the magnitudes of these various terms, an effort was made to discriminate whether the values indicated a high, medium or low potential for ice-related flooding. The criteria for ranking the terms are provided in Table 5.

Table 5. Ice jam potential rating factors.

Term	Range	Indicated potential	
		Low	High
Fahrenheit freezing degree-days	918 / 3300	<1700	>2600
FDD_{max}	135 / 180+	<150	>165
Q_{max}	145 / 175	<155	>170
$Q_{max} - FDD_{max}$	-13 / +30	<-8 or >+10	>-5 or <+7
Q_b (K cfs)	17 / 124	<25 or >90	>30 or <70
Garrison stage (ft)	1798 / 1844	<1835	>1840
Total snowfall (in.)	5 / 60	<20	>40
Snowfall timing	N.A.	<5 in. after JD=90	>10 in. after JD=90
		JD=90	> 5 in. after JD=120

Based on these criteria, values for the various terms that would indicate a high correlation with ice jamming are indicated by a "+" in the table, while values associated with a lesser risk are denoted with a "-." Note that three terms, FDD , $Q_{max} - FDD_{max}$ and snowfall magnitude, are double weighted.

In the final three columns the number of "+" and "-" symbols have been added and a ratio calculated. Values less than one would indicate lesser ice jam flooding potential, while values greater than one would indicate a greater potential. The lowest ratio for a known ice jam is 1.5 in 1978, but three years in which no jams were reported (1974, 1979 and 1984) have values greater than 1.5. The highest ratio, 5.00, occurred in 1984, which had no reported jam. However, the breakup period discharge was only 19,500 cfs, less than the flow required to initiate ice cover breakup. While these criteria are empirical and approximate (there is no precedent for this prediction scheme), their correlation with past ice jam events is quite clear. More importantly, tabulating these or comparable terms during future winter seasons should give a useful indication of the potential for ice-related flooding in the spring.

MITIGATION TECHNIQUES

While the winter of 1991-92 was warmer than normal and had less snowfall and no significant ice jamming, the ice breakup observed may still be indicative of breakup processes in a majority of years. We were able to identify only six significant ice jam events in the last 40 years, although more events may have occurred. For those years in which jams did occur, the weather was colder and/or snowier than average, and an increase in

runoff sufficient to cause breakup came when the ice was still thick and strong. Because of the low topographic relief within the Irrigation District, relatively small jams will cause overbank flooding, as the overbanks are generally within 5 ft or so of normal winter stages.

Techniques for mitigating ice-jam-related floods can be grouped into those measures that are designed and implemented to alleviate future problems and those that take place in response to a jam already in existence. Advance measures range from alteration of river ice formation processes to provisions for structural containment of ice and flood waters. Although the mild ice conditions encountered during 1991-92 required no response for mitigation of ice-related flooding, short-term advance measures would appear to be technically feasible. Since there are a relative few problem jamming locations in the study area, and in view of the smooth ice cover and favorable weather conditions, structural weakening of the ice (either mechanically or by dusting) could ease the passage of the ice run through these resistant reaches. Had the advance preparations failed and ice jams formed, emergency flood-fighting measures would also have been possible.

The smooth, single-layer ice sheet observed on the river during the winter of 1991-92 indicates that ice growth (and hence the total ice volume available to form a spring breakup jam) is dominated by thermal growth once the river is ice covered, rather than by accumulation or jamming processes during the freezeup period. Based on the observations of 1991-92 and the information collected in the historical review, it is clear that long-term mitigation techniques will have to focus on the spring breakup period rather than the control of ice formation. Basic flood control alternatives

could include ice retention to prevent or control breakup, flow containment or diversion to reduce flood damage, and ice weakening to reduce jamming potential.

Nonstructural techniques

The most common location for ice jams to form is in an area where the slope of the river changes from a steeper to a milder slope. Since gravity is the driving force for an ice run, when the ice reaches the milder slope it loses its impetus and stalls against a more stable downstream ice cover. Another common location for ice jam formation is the point where a tributary stream enters a larger river. Smaller rivers normally respond to increasing runoff more quickly than large rivers. The ice cover on a smaller river will typically break up and run until it reaches the strong, intact ice cover on the larger river, where the slope is normally milder as well. The ice run stalls at the confluence, forming a jam and backing up water on the tributary stream. Riverbends are also frequently cited as ice jam instigators. While riverbends may contribute to jamming by forcing the moving ice to change its direction and by causing the ice to impact the outer shoreline, slope is again a factor. Riverbends are nature's way of controlling river slope, with a straight reach between two points being the steepest possible course, and the slope decreasing as the bend severity increases.

On the Missouri River in the Buford-Trenton area, all three of these ice jam instigators are present. At the lower end of the District as the Missouri enters Lake Sakakawea, the energy slope decreases as the river enters the still waters of the lake. Near the upper end of the District, the Yellowstone River typically breaks up several weeks prior to the Missouri River, and the first ice jam in the vicinity of the District is often in the confluence area of the two rivers. Between these two locations the District is separated by a series of riverbends, two of which are common jam locations (Ryder and Hurley bends).

Since jamming in each of these areas arises when the ice run loses a portion of its driving force due to a reduction in slope, the situation might be improved either by increasing the driving forces or by reducing the resisting forces. First we will look at means of reducing the resisting forces by weakening the ice cover. Weakening the ice cover has been employed in numerous areas to reduce flood potential or to limit its severity. Methods of ice weakening can be grouped into

methods that mechanically weaken ice and those that speed ice deterioration.

Mechanical weakening

Ice weakening has been accomplished by using mechanical cutting techniques on rivers such as the Rideau in Ottawa, Ontario, and the Beau-rivage near Quebec City, Quebec, among others. Recently the Finnish National Board of Waters and Environment, through its District Office in the town of Kokkola, has been developing ice-cutting equipment for the purpose of mechanical ice weakening.* The prototype device has a cutting wheel 2.5 m (8.2 ft) in diameter and 0.2 m (0.66 ft) wide. It is towed behind a tracked, amphibious vehicle. In 30-cm- (1-ft-) thick ice it can cut ice at a speed of 4 km/hr (2.5 mph). With 60-cm ice the speed is reduced to about 2 km/hr (1.25 mph), and with 120-cm ice the speed is approximately 1 km/hr (0.6 mph). Once testing is complete, they plan to have these ice cutters manufactured and marketed commercially.

As reported in Deugo (1973), ice cutting is an annual activity on the Rideau River in Ottawa, Ontario. A 7.5-mile reach above the confluence with the Ottawa River is cleared of ice during a two-week period beginning in late February in anticipation of the spring freshet. Ten thousand lineal feet of ice are cut in critical locations during this time using a mechanical saw. They are able to clear 7.5 miles of river with only 2 miles of actual cutting. The unit is a circular saw powered by a 60-hp engine and is capable of cutting to a depth of 2 ft. The ice cutter is used to cut slots parallel to the water flow approximately 50 ft from each shoreline. Once cutting is complete and spring runoff approaches, explosives are used to dislodge the ice cover throughout the reach, beginning at the downstream end. The combined costs of the cutting and blasting program in the City of Ottawa is approximately \$180,000 in 1985 Canadian dollars.

In relatively straight reaches of a river, simply cutting slots down both sides of the river to release the ice cover from the riverbanks may be sufficient, while in curved reaches more elaborate cutting patterns may be required. Jolicoeur et al. (1984) reported on tests of ice trenching performed in an effort to find a cheaper, safer and more environmentally acceptable alternative to the explosive demolition of ice. In those tests a series of five cutting patterns were used to allow

* Personal communication, M. Ferrick, CRREL.

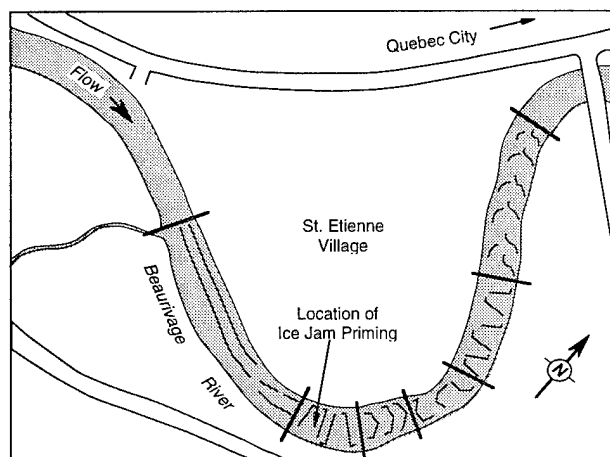


Figure 8. Map of Beaurivage River ice cutting. (After Jolicoeur et al. 1984.)

an evaluation of their performance in a river-bend. A general map of the area along with a depiction of the cutting patterns is shown in Figure 8.

The patterns were cut in the ice using an unmodified Case DH4 trencher. This trencher has a chain width of 15 cm and an in-line trenching speed of about 8 m/min (26 ft/min). Trenching a 600-m (2000-ft) bend using the five patterns took eight hours, or a normal working day. Although all cutting patterns worked well, the authors felt that the most efficient pattern was the one consisting of an unconnected "V" pattern shown farthest downstream in Figure 8.

Jolicoeur et al. (1984) concluded that trenching breaks more ice than blasting, costs about a third as much, has no adverse environmental effects and is far safer. Ice trenching has been used as an advance measure on the Beaurivage River annually since 1984.* Because significant ice strength is required to support the large trenching machine initially employed, ice cutting on the Beaurivage River since 1986 has been conducted with a specially designed "Aquadglace" ice trencher that was lighter and safer to operate on thin or weak ice (Belore et al. 1990).

Each of these reports has discussed ice cutting that involved completely cutting through the ice, allowing the cut slot to fill with water. With the smooth, uniform ice sheet present in the Buford-Trenton area, however, it would be possible to cut a trench that doesn't quite penetrate the cover, allowing the slot to remain dry. This would be an advantage if cutting were conducted early

enough in the season such that water in the trenches could freeze and defeat the operation. On the other hand, if warm sunny weather was anticipated, the slots could be cut completely through the ice since the low albedo of water in the trenches could absorb additional solar radiation, leading to accelerated ice decay.

Ice deterioration

Ice deterioration occurs both through thermal melting and through decay of its internal structure. With higher air temperatures, higher sun angles and longer days in the spring, the winter snow cover and the top surface of the ice begin to melt, forming a water layer. With the reflective snow cover gone, this water layer absorbs more solar radiation, and deterioration of the ice structure along crystal boundaries can take place. The ice becomes progressively thinner and weaker, and given time the ice will melt in place.

One technique that has been used to accelerate the decay of an ice cover is dusting. The term dust is used here to denote any dark material that can be spread on the ice in a thin layer so as to absorb solar radiation and thereby accelerate the deterioration process. Dusting has been used in the Omaha District to reduce ice-related flooding potential on the Platte River in Nebraska (USACE 1979). Moor and Watson (1971) described the use of dusting on the Yukon River in Alaska. They found that dusting a river reach subject to perennial jamming two to three weeks prior to breakup weakened the ice sufficiently so that no jams formed there during years when dusting was performed. Ideally the dust should be applied as early as possible to provide maximum deterioration time but after the last snowfall (which would cover the dust and render it useless).

Dusting materials can include such substances as fly ash from the burning of coal or pit run sand. Moor and Watson (1971) suggested an application rate of 0.5 lb/yd² for sand and 0.35 lb/yd² for fly ash. Sinotin (1973) cited values of 0.18 lb/yd² for 0.04-in. material and 0.92 lb/yd² for 0.2-in. material. Problems with aerial dusting identified by Moor and Watson (1971) include moisture (the material must be dry enough to flow freely and not freeze), wind (even a slight breeze can cause drifting of fine materials and require low release altitudes) and ice or glazed snow surface (the dust can drift after landing). The potential for adverse environmental impacts of the dusting material must also be considered.

Instead of aerial dusting, it is also possible to

* Personal communication, B. Michel, Universite de Laval, Quebec City, Canada.

pump a slurry of water and riverbed sediments onto the ice, at least for rivers with silt or sand bed material. Moor and Watson (1971) described tests in which dusting coverage similar to aerial dusting was obtained by pumping. While the cost of treating a 100-ft-wide strip was less than for aerial application (\$0.09 per lineal foot in 1970 dollars), a disadvantage is the time required to cover large areas, as required in most ice jam prevention applications.

Flow control

The control of river discharge has been used both to increase ice cover stability and prevent jamming and to intentionally cause river ice breakup. Flow control is often used during the fall freezeup period to allow a thinner, more stable ice cover to form in a reach where natural flow velocities would cause ice floes to overturn or shove and thicken into a jam. This form of flow control may also be used to improve the performance of ice control structures by providing reduced, steady flows during ice cover formation (Deck 1984). Similarly, flow control during the spring could be used to prevent ice cover breakup, delay breakup until significant deterioration of the ice cover has occurred, or reduce peaks in water discharge and resultant flooding. This approach, however, requires a dam with sufficient storage capacity located near enough to the flooding problem area.

In the case of the Buford-Trenton area, flow control is employed by Fort Peck Dam on the Missouri to reduce flood peaks during the breakup of the Yellowstone River. This also increases the tendency of the Missouri River to break up several weeks after the Yellowstone River and limits the supply of ice feeding any ice jams that might occur within the Irrigation District during the breakup period on the Yellowstone River. During the 1986 event, Fort Peck releases were reduced from 12,000 cfs on 1 March to 1,000 cfs on 9 March to lessen flooding (USACE 1986). Unfortunately Fort Peck is far upstream from the Buford-Trenton area and can control only a small portion of the flow causing flooding (the drainage area above Fort Peck Dam is 57,500 mi² vs. 164,500 mi² above Williston). Further, close monitoring of conditions on the Yellowstone is a must, since the travel time of water from Fort Peck Dam to the District (about 200 river miles) is on the order of four days.

Flow control, in the form of a rapid increase of discharge from a dam, has also been tested as a

technique to fracture an ice cover and cause premature breakup (Ferrick and Mulherin 1989). The rapid release of a pulse of water is intended to cause the ice cover to fracture and run with a smaller increase in stage than required for most natural runoff events. This method could be helpful in the case of a tributary stream that jams as it encounters an intact ice cover at its confluence with a larger river. With adequate flow control on the larger river, it might be possible to cause the ice on the larger river to break up prior to the smaller river, providing room for the smaller river's ice run to enter. The dam release must be quite rapid and near to the problem site so that a sharply defined wave passes through the ice. Although clearing the ice cover on the Missouri River prior to breakup on the Yellowstone River should reduce the threat of ice jam flooding, Fort Peck dam is much too far away to provide such a pulse of water.

Icebreaking

Icebreaking is another nonstructural alternative for clearing a channel or weakening its ice cover in advance of a natural breakup. As described in the flow control section above, icebreaking on the Missouri River in advance of the breakup of the Yellowstone River ice cover would help mitigate ice-related flooding. The use of icebreaking ships is highly effective but requires suitable vessels on-site, which is not the case in the Buford-Trenton area. In rivers that are isolated from navigable waterways or too shallow for navigation by icebreaking ships or tugs, air-cushion vehicles (Kankakee and St. Lawrence Rivers) or amphibious landing craft (Buffalo River) have also been used.

Early warning

While not a flood mitigation measure, an early warning system can be quite useful in minimizing flood losses. The ice jam potential rating scheme presented earlier can be used to provide some indication of whether ice-related flooding is likely. In addition, there are numerous water level gages along the Missouri and Yellowstone Rivers in the vicinity of the Irrigation District that are either no longer in use or not active during the winter months. Reactivating gages in the District and for a good distance upstream, and adding telephone, radio or satellite relays, could provide an early warning system for increased flows, ice movement or increasing stages. Direct ice motion sensors could also be added to the gaging stations

to indicate the onset of ice motion leading to breakup of the ice cover.

Structural measures

Structural control measures include the construction of permanent or temporary structures either to prevent ice-related flooding or to lessen damages should a flood event occur. Such measures include means to control ice formation, restrain ice movement, and contain or divert flood flows, either alone or in combination.

Flood containment

Flood containment normally refers to levees that physically separate the river from property to be protected. While levees are expensive and normally limited to the protection of densely populated areas, the Buford-Trenton area is currently protected by the levee-like irrigation ditches. The level of protection against ice-related flooding provided by this system of ditches is unclear. The 1986 ice jam event nearly overtopped the ditches in both the Middle and West Bottoms. The maximum flow during that event was approximately 60,000 cfs, well below the two-year open-water discharge of 90,000 cfs and somewhat less than the five-year breakup period discharge of 67,000 cfs. Their function as flood protection levees might be economically upgraded by identifying sections vulnerable to overtopping and raising them to provide a more uniform level of protection along the length of the system.

Ice control structures

Fixed structures can be used to stabilize an ice cover or prevent the downstream movement of broken ice. Stabilization of an ice cover prevents premature breakup, allowing additional time for the ice cover to weaken and melt in place and reducing the supply of ice for jamming downstream. Perham (1983) reviewed a wide variety of ice sheet retention structures, including pier-

mounted booms, stone groins, artificial islands, timber cribs, dams and weirs.

An ice control dam obstructs the passage of ice and can provide a reservoir to control ice until it eventually melts. Weirs and low-head overflow dams raise upstream water levels and promote stable ice covers upstream. At some sites they can also aid in controlling ice breakup in a manner somewhat similar to dams. A 9-ft-high overflow weir was built for ice control on the Israel River in New Hampshire by the New England Division of the Corps of Engineers (USACE 1973, 1982b). The 170-ft-long weir was constructed with concrete-capped gabions, with four, 4-ft-wide by 8-ft-deep gaps to allow fish passage during the open-water months. During the winter the gaps are blocked with stop logs or metal gates to develop an ice retention pool (Axelson 1991). Completed in 1982, the project cost \$300,000, for a unit cost of about \$1800/ft.

An ice control structure consisting of a 5-ft-high fixed-crest weir with a Bascule gate for sediment passage was constructed on Oil Creek by the Pittsburgh District of the Corps of Engineers in 1989. The structure was 351 ft in length, including the 45-ft-wide gate, and had a supplementary ice boom located 75 ft upstream to increase its ice retention capability. Levees were constructed on both upstream banks to contain the Standard Project Flood. The total project cost was \$2.2 million, for a unit cost of about \$6300/ft.

A low-head (6-ft) weir for ice breakup control has been physically modeled and designed for Cazenovia Creek near Buffalo, New York (USACE 1985, Gooch and Deck 1990). As shown in Figure 9, the proposed weir has nine ice retention piers rising above its crest and is bordered by a high-level, bypass floodway to help limit hydraulic forces that could cause the upstream ice to be extruded through the piers. This project, designed by the Buffalo District of the Corps of Engineers, has an estimated cost of \$2 million. With a struc-

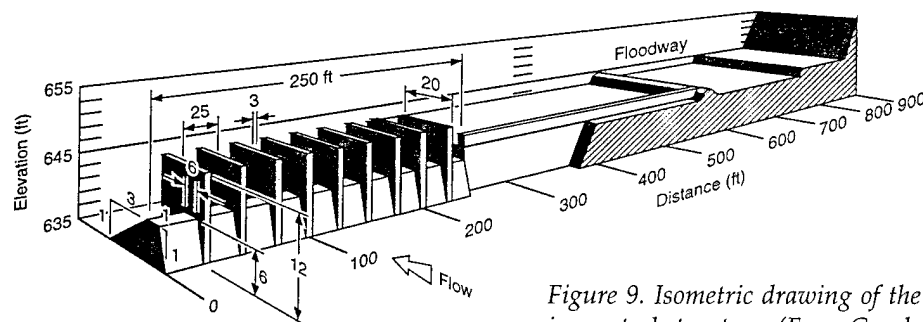


Figure 9. Isometric drawing of the proposed Cazenovia Creek ice control structure. (From Gooch and Deck 1990.)

tural width of 650 ft, the cost would come to about \$3100/ft, but the project cost also includes excavation to enlarge the pool upstream of the structure as well as the construction of a 200-ft-wide floodway to route flows around the structure at higher discharges.

Belore et al. (1990) described an ice control structure on the Lower Credit River in Canada consisting of concrete piers placed at approximately 7-ft spacings across the main river channel. The structure was designed to stop the downstream movement of ice at breakup and make use of the available channel and floodplain storage.

Ice booms, the most widely used type of ice retention structure, are essentially a series of logs, timbers or pontoons tethered together and strung across a river to control the movement of ice (Fig. 10). In some locations, however, the boom elements are supported by fixed piers. Ice booms are most commonly used to stabilize or retain an ice cover in areas where flow velocities are 2.5 ft/s or less and relatively steady.

While conventional ice booms are normally used to promote ice cover formation during freezeup and during midwinter in areas of marginal stability, if properly designed they can have application in some breakup situations. The Lake Erie ice boom located at the head of the Niagara River has been employed for many years to keep lake ice floes from passing into the river, causing flooding and disrupting hydroelectric plant operations. Perham (1983) recounted a description of an experimental ice boom built on the Chaudiere River in Quebec:

The boom was like a horizontal rope ladder with steel structural channel sections for rungs. The spaces between the rungs were filled with wooden blocks. The two parallel 25-mm-diameter wire ropes were anchored to heavy concrete structures at each shore. The arrangement was expected to retain ice until a flow of 207 m³/s (four-year flood) was reached.

Costs for ice booms can vary with river size and ice conditions. Table 6 summarizes the costs for a number of flexible ice boom installations as compiled by Perham (1976). The costs listed have not been converted to a common year but correspond to costs at the time of design and construction as indicated in the table; costs for structures in Canada are in Canadian dollars. The only Corps of Engineers structure is the St. Marys River ice boom, which had a unit cost of about \$212/ft of river width spanned in 1975. More recently the Pittsburgh District constructed the Allegheny River ice boom shown in Figure 10. This boom

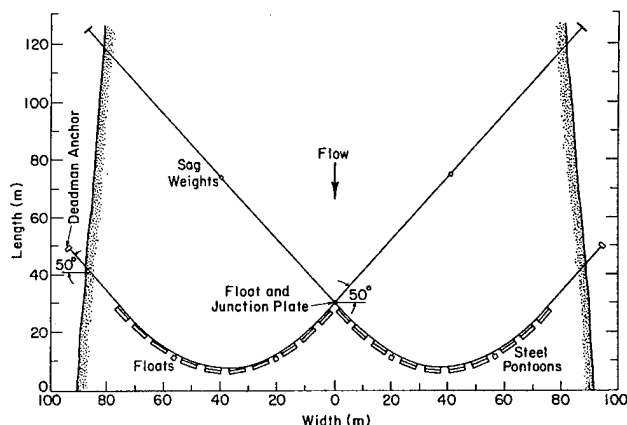


Figure 10. Plan view of the Allegheny River ice boom. (From Perham 1983.)

Table 6. Summary of costs for existing ice boom installations. (After Perham 1976.)

Body of water	Length (ft)	Year	Cost (\$M)	Unit cost (\$/ft)
St. Lawrence River, Ogdensburg, New York—Prescott, Ontario	16,830	1960	0.8	48
Lake Erie, Niagara River, Buffalo, New York	8,800	1964	0.9	103
Beauharnois Canal, St. Lawrence River, Beauharnois, Quebec	17,000	1964	1.5	92
Copeland Cut, St. Lawrence River, Massena, New York	750	1974	0.25	333
Riviere des Prairies, Montreal, Quebec	2,300	1975	0.25	109
Lake St. Francis, Valleyfield, Quebec	7,200	1975	2.0	278
St. Marys River, Sault Ste. Marie, Michigan	2,400	1975	0.5	212

cost approximately \$900,000 to construct in 1982. It spans a river that is 540 ft wide, for a unit cost of about \$1700/ft. The Montreal ice control structure, on the St. Lawrence River, is a rigid ice boom that uses floating steel booms or stop logs set between concrete piers to collect ice floes and stabilize an ice cover. The 1.27-mile-long structure cost approximately \$18 million in 1964-65 (Perham 1983), or about \$2700/ft.

Groins, dikes or jetties can be used to constrict channel width, raise water levels and reduce upstream velocities to promote the formation of a stable ice cover (Cumming-Cockburn and Associates 1986, Janzen and Kulik 1979). Sometimes the ice retention capacity of such structures is enhanced

with upstream ice booms (Perham 1983). At breakup the reduced river width can improve the stability of unfrozen ice accumulations, making them thinner and less of an impediment to flow, and it might even prevent breakup of the solid ice cover (Cumming-Cockburn and Associates 1986). Such structures can also create a storage area for ice floes at breakup, reducing the volume of ice passing downstream. Opposing dikes have been used for ice control on the Burntwood River in Manitoba and on the Pasvik River in Norway (Perham 1983, Janzen and Kulik 1979).

Artificial islands of soil or rock or both have also been employed in many areas, including the St. Lawrence River near Montreal, to help hold ice in place, just as natural islands often do (Perham 1983). A smaller variation on the use of artificial islands is the construction of stone-filled timber cribs to anchor an ice sheet. An example of using timber cribs for controlling ice can be found on the Narraguagus River in Cherryfield, Maine (Perham 1983). Three cribs, oriented in a triangular pattern, are located about 125 ft upstream of a 7-ft-high dam and spillway.

A longitudinal dike or series of structures aligned with the flow along the center of a channel can be employed to decrease the effective width of a river (Cumming-Cockburn and Associates 1986). Since the river width that an ice cover or accumulation must arch across is reduced, stability is increased and a thinner cover with lower water levels may result. Channel divider structures can be used to promote early ice cover formation, delay ice cover breakup, and initiate and maintain stable breakup accumulations at desirable locations. A divided channel design was incorporated into the Burntwood River diversion project in Manitoba (Cumming-Cockburn and Associates 1986).

Channel modifications

Ice jams tend to form in areas of change in slope, riverbends, slow-moving pools and constrictions. Channel modifications can be used to improve the passage of ice through such reaches. An example of such a channel modification can already be found in the Buford-Trenton area in the form of a channel cutoff constructed by the Corps of Engineers in the late 1950s between cross sections 1569.24 and 1574.16. This cutoff isolated a sharp riverbend, eliminating a long length of channel and significantly increasing the local slope. Such cutoffs must be used with care, how-

ever, due to both the potential adverse effects on river morphology and the possibility that a new ice jam location may be created downstream where the artificially steepened cutoff reenters the natural channel.

Another form of channel modification is a diversion channel to divert excess flood waters around a jam or beyond an area to be protected. A diversion channel can also be used in conjunction with an ice control structure to improve its performance. For example, if an ice control dam or weir were used to control a breakup ice run, a high-level diversion could be used to limit the discharge reaching the structure, reducing river stages to prevent local flooding and ensuring the stability of the ice being retained. Such a diversion can be designed to remain dry except during flood events so that it will be available to function as an open-water channel and not add to the ice supply reaching downstream ice jam sites.

Instead of diverting excess flood waters, it is also possible to divert or store ice during breakup in areas where it will cause less damage. Even without human intervention, significant volumes of ice are often left behind during an ice run in side channels, on floodplains or simply grounded on the riverbanks. By developing low overbank areas where ice can easily leave the channel during breakup, perhaps supplemented by dikes or booms to redirect ice movement, the volume of ice passing downstream can be substantially reduced.

Ice anchors are an additional form of channel modification that can be used to control ice. While ice control dams and weirs are constructed to slow the flow of water by raising water levels, ice anchors are essentially pools excavated in rivers to help stabilize ice during formation or breakup. During freezeup the pool can help to form an ice cover early in the winter season and obstruct the passage of ice floes to downstream areas. During the breakup period the pool can serve to moderate stage fluctuations caused by rising discharge, thus maintaining a stable ice cover in a manner similar to an ice control weir or dam. An ice anchor constructed on the Bow River near Calgary, Alberta, involved the excavation of about 140,000 yd³ of bed material, resulting in a pool approximately 650 ft long, with a top width of about 330 ft and an average depth of about 11 ft (Andres and Fonstad 1982). On rivers with significant transport of sediment, however, such dredged pools could be refilled and rendered useless in a short period of time.

Thermal control

Thermal ice control methods use either heat obtained from a nearby source (such as power plant cooling water) or heat contained in the water body itself to melt ice. Because water reaches its maximum density at a temperature of about 39°F, colder water in lakes tends to stratify above warmer water. An ice cover can form on the water surface even though the water at depth is still well above freezing. When present, this warm water can be brought to the surface quite economically using air bubble, pumps or flow enhancers. While this natural source of warm water is common on lakes and reservoirs, warm water can exist at depth on some slow-moving rivers as well. Water even a fraction of a degree above freezing can be quite effective in melting ice over a period of days or weeks. With water velocities on the order of 1–3 ft/s in the Missouri, however, such a warm water source is unlikely except downstream in Lake Sakakawea.

External heat sources can include the cooling water effluent from fossil or nuclear power plants, or even groundwater. Recently a thermally based ice control solution was developed on the Kankakee River near Wilmington, Illinois (Deck 1986). A siphon system was constructed to extract warm water from a nuclear power plant's cooling pond and place it in the river through a system of diffusers. Unfortunately no ready source of warm water is available in the Buford–Trenton area.

Emergency measures

Predicting when, or even if, an ice jam will occur at a given location in a given year is rarely possible. The section dealing with ice jam potential provides a scheme for predicting whether ice jams are likely in the Buford–Trenton area based on weather and flow conditions, but should ice jams occur unexpectedly or in an area where no advance measures were taken, it may be necessary to resort to so-called emergency measures. Once a jam is in place, there are generally few mitigation alternatives available. The Ice Engineering Manual (USACE 1982a) cites four methods: mechanical removal, dusting, blasting and icebreaking with ships. Dusting has already been discussed as an advance measure, but because of the time required for dusting to be effective, it is not normally effective once a spring breakup jam is in place. The use of icebreaking ships is highly effective but requires suitable vessels present on-site, which is not the case in the Buford–Trenton area.

Blasting, in an appropriate application, can be

quite effective. However, the primary purpose of blasting is to break an ice cover or to loosen an ice jam so that it is free to move, and there must be enough flow passing down the river to transport the ice away from the site and an open-water area downstream to receive the ice. Since the primary driving force available to break ice by blasting is the large gas bubble resulting from the blast and not the shock waves, the charges must be weighted and placed under the ice cover. Blasting is not a quick, easy solution. It requires planning, acquisition of explosives and hole-drilling equipment, and a crew of perhaps 11 people (USACE 1982a). A properly outfitted crew might be able to blast two rows of charges along about one-half mile of river per day. Safety and environmental concerns must also be addressed.

Removing an ice jam mechanically simply means taking the ice out of the river and placing it elsewhere. This method directly relieves the cause of flooding but is neither cheap nor fast. In February 1978 it cost approximately \$11,500 to make a 2600-ft channel with a backhoe (USACE 1982a). Other mechanical removal operations have employed such equipment as bulldozers, excavators and draglines. Because of the time required to excavate ice with conventional equipment and safety concerns, this approach is normally limited to midwinter jams on small streams.

Mitigation techniques for the Buford–Trenton Irrigation District

A number of ice-related flood mitigation techniques have been reviewed in terms of technical, but not economical, feasibility. Given the climate of the Williston area and the characteristics of the river ice regime, a program of ice weakening should be feasible as either a short-term advance measure or a long-term ice control program. Ice weakening efforts should be focused on the river bendways near Ryder Point and the Hurley Bend, which have been frequent jam locations in the past. In terms of structural control measures, flood flow containment is already a reality for a flow approaching a five-year recurrence interval spring breakup flood due to the existence of the raised irrigation ditches along much of the river in the Buford–Trenton Irrigation District. It might be possible to improve the level of protection offered by these ditches by raising low spots and ensuring their structural adequacy.

The confluence area of the Missouri and Yellowstone Rivers is considered to be a good poten-

tial site for controlling ice during breakup. According to local residents, problem breakups typically consist of a 0.5- to 2-mile-long jam (though sometimes as long as 4 miles), which propagates slowly in a series of jam and release cycles down the Yellowstone and continuing into the study reach on the Missouri River. Flood flows and ice breakup on the Missouri River generally occur several weeks after the Yellowstone River ice run. One of the natural jamming points for the Yellowstone River ice run is in the confluence area, and based on interviews with local residents concerning jams in that area, the jams have not caused significant damage in the past. Causing the jam to remain in this area would surely alleviate downstream ice jam flooding. Ideally the ice should be retained and allowed to melt at this site. The observation that the spring breakup ice run propagates tens of miles while the jams remain relatively short and constant in length indicates that significant melting is a common feature at breakup and can be used to advantage in conjunction with structural control.

Numerous types of structures or stream alterations could be used for ice control in the confluence area. Rock-filled timber cribs, spur dikes, ice control weirs, ice booms and a dredged ice retention pool are potential alternatives. If necessary a high-level flood bypass or diversion channel could be incorporated into the design to ensure proper performance of the structure and to reduce flood levels in the vicinity. Numerous existing water level gages that are either inoperable in winter or totally abandoned could be used as sites for detecting ice movement and providing advance warning of breakup or flooding.

Most ice control projects pursued by the Corps of Engineers in the past have been conducted under the general authority of Section 205 of the 1948 Flood Control Act, as amended. That act authorized the expenditure of funds for the construction of small projects for flood control and related purposes not specifically authorized by Congress. More recently the Water Resources Development Act of 1986, Title XI, Section 1101 (U.S. Congress 1986) directed the Secretary of the Army to undertake a program of research and community assistance for the control of ice and ice-induced streambank erosion. Further, the act authorized the Secretary of the Army to:

...provide technical assistance to units of local government to implement local plans to control or break up such ice. As part of such authority, the Secretary shall acquire necessary

ice-control or ice-breaking equipment, which shall be loaned to units of local government together with operating assistance, where appropriate.

The act also authorized and directed the Secretary of the Army to undertake a series of demonstration projects for the structural control of ice, projects that were to be exempt from the cost-sharing provisions of Section 103 of the Water Resources Development Act of 1986. Under this act the Corps of Engineers would have been authorized and funded to assist local communities in analyzing their ice-related flooding and streambank erosion problems, develop measures to control ice and mitigate damages, and lend specialized "ice-breaking" equipment that could have been used to implement some of the advance or emergency measures described above. At some sites, structural ice control measures would also have been implemented. Unfortunately the necessary funding was never appropriated.

SUMMARY AND CONCLUSIONS

This report has reviewed historical and recent information on ice processes and ice-related flooding in the vicinity of the Buford-Trenton Irrigation District near Williston, North Dakota. Based on that information, an evaluation of the ice regime of the Missouri and Yellowstone Rivers was conducted to assess the potential severity of ice-related flooding. A scheme for estimating the potential for ice-related flooding in any given year was outlined, along with a suggestion that existing water level gages be reactivated for winter activity to provide an early warning mechanism for ice breakup and flooding. Finally, a number of structural and nonstructural flood control measures were reviewed from a technical applicability standpoint. Mitigation techniques recommended for further, detailed study include a program of ice weakening in advance of spring breakup, improvements to existing irrigation ditches to allow them to afford an increased level of protection as pseudo-levees, and structural ice control or diversion on the Yellowstone River near its confluence with the Missouri River.

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